

USNA PHYSICS: SPEED OF LIGHT EXPERIMENT

Construction and Instructor Notes

Instructor Notes: THERE ARE FOUR SETUPS

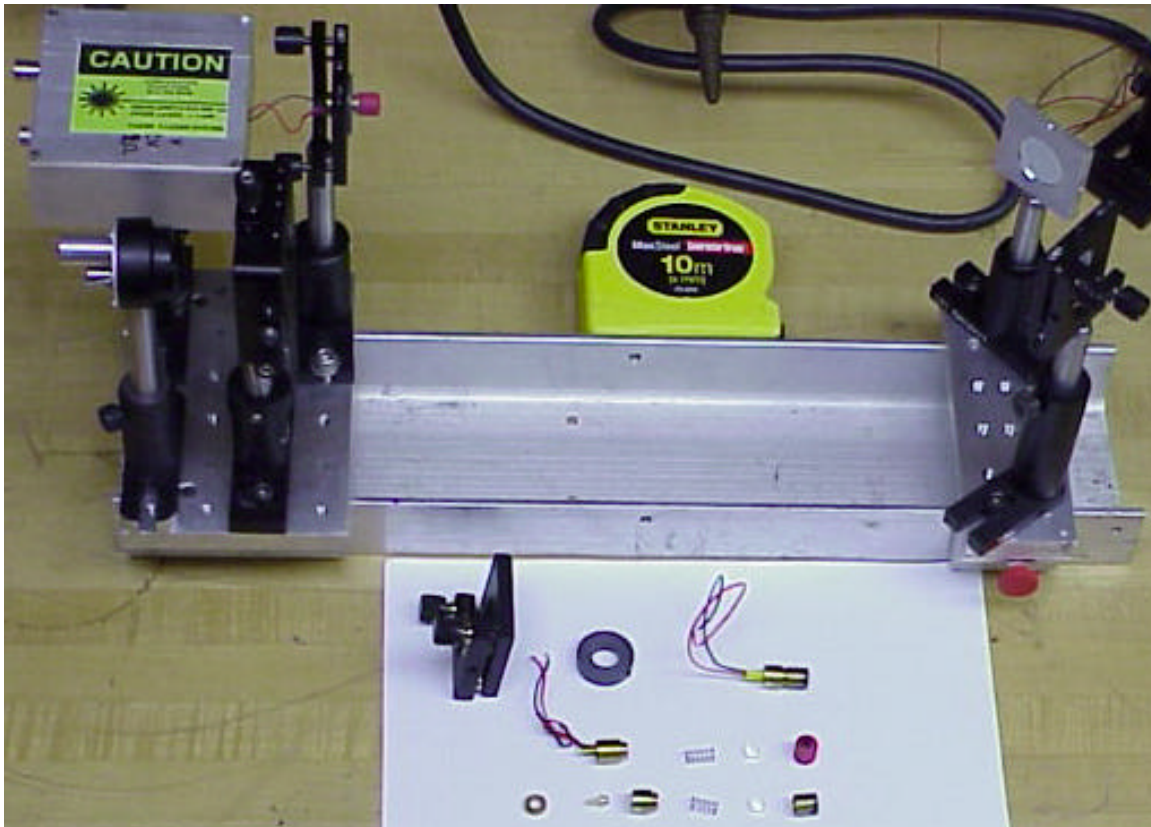
Purchase at least four (4) fresh A23 size 12 volt batteries. These are standard Photo batteries. The POSITIVE terminal of the battery is to be toward the detector circuit board. Reversal would forward bias the photodiode killing it.

The Laser Drive Monitor is to be terminated at high impedance. This is a *suggestion* as the monitor will drive a 50 Ohm input. It does however stress the circuit and is rarely needed. Just set the trigger at the 50% level on the monitored drive pulse to provide a solid timing reference for the experiment.

The laser pulse detector line must be terminated at 50 Ohms. A signal level of 20 mV is expected.

The power inputs for the drive electronics are not protected. Incorrect connections or over voltages can (and probably will) blow out several components including the laser diode.

A 200 MHz digital oscilloscope is an outstanding match for this experiment. The small 60 MHz digital scopes from Tektronix for < 1000\$ work well.



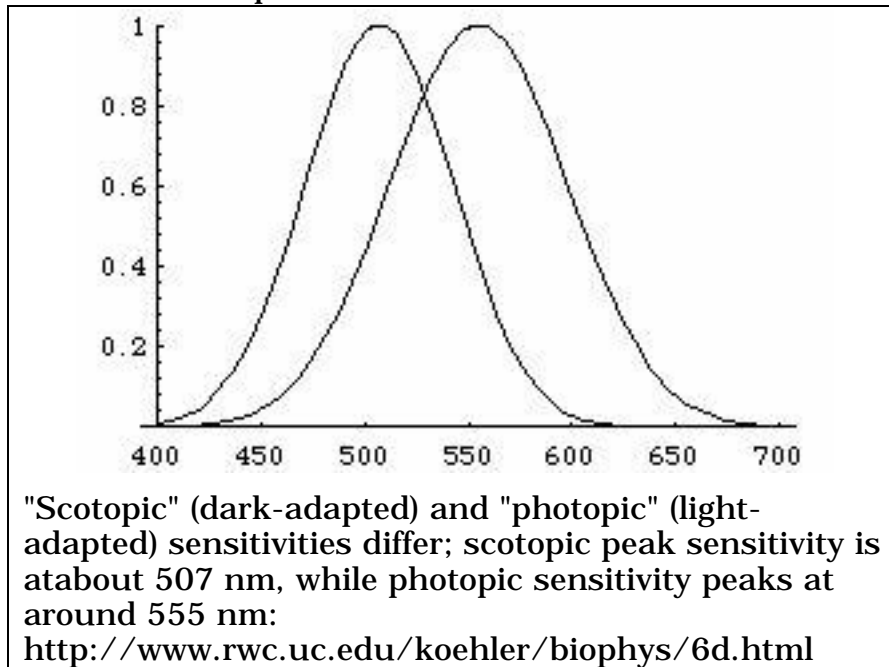
Goals:

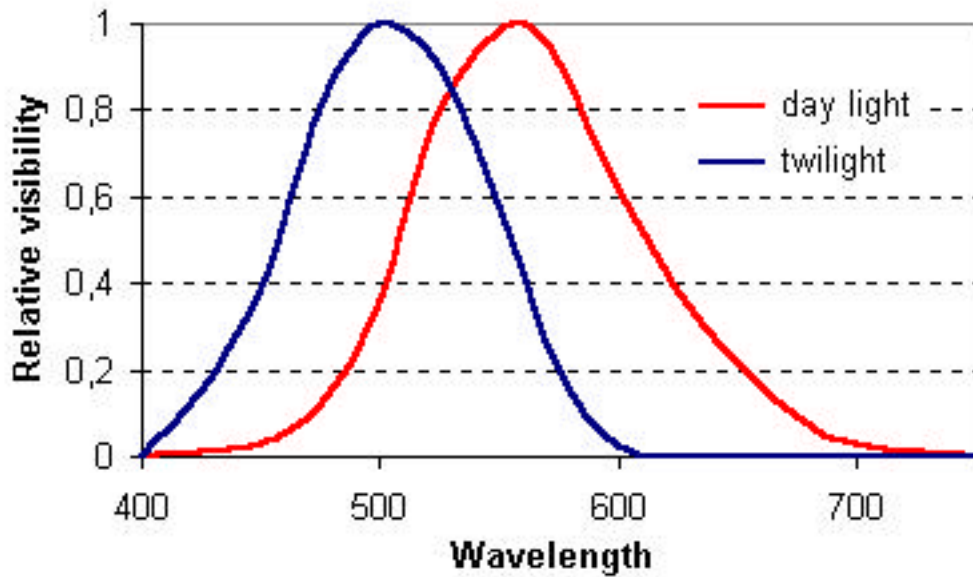
To measure the speed of light in air to within 2% and the propagation speed of electrical pulses along an RG58 coaxial cable. To require the students to practice alignment procedures necessary for almost all optical measurements.

Background:

The laser diode used in this experiment emits coherent light when the forward current through it reaches a threshold value of about 30 mA. Maximum intensity is reached for a current of about 35 mA, and, by the time the current reached 40 mA, the device overheats resulting in catastrophic damage to the facets (the smooth faces through which the light exits the diode) and drastically reduced light output and quality. The drive electronics should deliver a 20 MHz 'square-wave' current of the correct amplitude to drive the laser. The 50 ns period of the drive monitor should be used to check the oscilloscope time base. The period will be a multiple of 50 ns for units with the SN7497 option.

The laser power is set to about 500 μ W and warrants a Class II Laser Safety CAUTION rating. The beam is 'bright' and someone painful to if viewed directly, but it should not cause permanent damage if the viewer does not suppress the natural blink response. DO NOT STARE INTO THE BEAM. The 650 nm light has lower visibility than that of a HeNe so the brightness is a bit deceptive.





http://www.infoline.ru/g23/5495/Physics/English/rgb_txt.htm
 This figure shows the relative spectral sensitivity of the eye in daylight and twilight. Maximal sensitivity to the daylight is achieved at a wavelength of 555 nm, while in the twilight the maximal sensitivity of the eye is shifted to a wavelength of 510 nm. The maximal visibility is taken as a unit. The difference of these two curves can be explained by the fact that different receptors of the eye are working in the daylight and twilight. We can see in the figure that the eye can perceive light at a wavelength of about 400 nm to 760 nm. In darkness, the eye adapts so that we can slightly see infrared light at wavelengths up to 950 nm and UV light at wavelengths as low as 300 nm. This visibility spectrum range is limited by natural factors. Our atmosphere's ozone layer absorbs all the rays at wavelengths shorter than 290 nm, while the eye itself radiates strongly in the IR spectrum region. If the sensitivity of the eye in the IR region were the same as to green light, for example, the eye's own IR radiation would interfere with the visible IR light.

The electronics box is wired directly to the laser to provide drive current, and it provides a reference timing signal at a BNC connector. The signal on this BNC is a reduced copy of the drive voltage to across the laser diode and a series dropping resistor.

The fast photo-detector also has a BNC connector which monitors the optical power incident in the 0.8 mm diameter active area of the detector. A lens of focal length 50 mm (75 mm would be better !) focuses the beam to a spot smaller than the active area, and the adjustments on the lens mount facilitate positioning the focal spot on the active area. The photodiode is reverse biased with a 12 volt battery (type A23) and must be connected to an oscilloscope input terminated at 50 Ohms. A higher input resistance (impedance) would yield an RC time constant longer the

few nanoseconds necessary for this experiment. Driving the 50 Ohm load depletes the battery rapidly. TURN THE DETECTOR OFF when not in use.

Procedure:

The experiment as configured on an 18" aluminum C channel 4" wide. The oscilloscope traces included in this document were taken using this piece of C channel. The students use 25' aluminum I beams (just because we happened to have them) for the experiment. A 8-10' beam is recommended. It could be a wood 4x4. Note: the tape measure is metric.

Alignment:

Move the mirror set to a position about 2 meters from the laser diode (LD). Adjust the kinematic mount for the LD to direct the beam parallel to the edge of the track and so as to maintain a constant height above the track. Adjust the laser lens by rotating the front cylindrical portion of the laser which is a threaded lens cell. The beam size at the first mirror (M1) should be a few mm in diameter. Position and orient the first mirror such that the beam strikes the mirror near its center reflecting the beam at 90° across the carrier mount for the mirrors. The second mirror (M2) is to be adjusted to return the beam down a constant height path parallel to the track over the centerline of the mounting holes below the photo-detector (PD) centerline. (Remove the lens in its lens cell with post during this part of the procedure.) The height of the return beam may differ from that of the outgoing beam due to the crude mount for the M1. Adjust the laser lens to set the beam size at a few mm on the face of the detector. Adjust the kinematic mount for M2 to center the beam on the active area of the PD.

Repeat the process of aligning the outgoing and return beams while leaving the laser diode lens fixed. Note that the lens has a flat (plano) side and a curved (convex) side. The flat side is to be nearer to the PD. Examine the lens cell mount and center its adjustment screws. Return the lens cell to its mount and adjust its height and 'left-right' position to center the focused beam on the PD. DO NOT use the adjustment screws on the lens cell for this part; just do your best with the height adjustment of the post and positioning of its post holder.

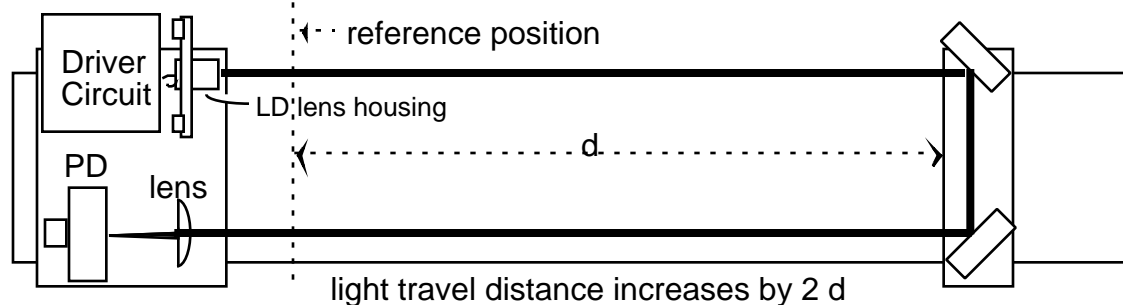
The active area of the PD has a diameter of less than 0.8 mm and is harder to hit than you might think. You will use the vertical and horizontal adjustment screws to scan the spot onto its active area. One method is to find the positions at which the spot is too far left and then too far right and to set the adjust at their midpoint. Repeat for the vertical adjustment. Next you scan carefully searching for the detector's sweet spot. One person should be monitoring the oscilloscope trace because, once any signal is displayed, one can adjust the positioning screws to maximize the signal. (Detector switch ON; Oscope input 5 mV/div, 10 ns/div, 50 Ohm. ** Use high impedance settings except for the detector line) There is another most intriguing feedback signal. The detector generates its signal by absorbing the light to excite electrons into the conduction band. When the beam strikes the active

area, it is as if the detector sucks it in ! When the beam is on the active spot the intensity of the reflected and scattered light is noticeably diminished.

Measurements:

Connect the drive monitor output to Ch1 of the scope. High impedance, 1 V/div, 10 ns/div. Trigger of CH1 with the trigger level at the 50% level on the drive pulse. Connect the photo-detector to Ch2, 5mV/div, 50 Ohm. Set the cursor readout to TIME. Adjust the sensitivity settings as appropriate. Read the cursor times on the 5 ns/div sweep rate.

I. Speed of Light: Set the mirror pair at a reference distance close to the source and detector. Find and maximize the light signal. Set the time cursor at a reference feature on the light signal. Record the time. Move the mirror set away recording the distance d and cursor time for the light signal reference feature for each value of d . Return the mirror set to the original reference position and repeat the time measurement.



II. Electrical Signal Speed: Keep the mirrors fixed at the reference position with the light signal maximized. Remove the detector BNC connection from the oscilloscope. Attach a short cable to that input. Use two barrel connectors to join the cables with a short 'speed of signal' cable. Measure ℓ , the length of this cable between its connectors. Record the cursor time of the reference feature. Substitute 'speed of signal' cables of differing lengths recording ℓ and the cursor time for each.



Exercises:

The drive circuit waveform has a frequency of 20 MHz. What is the period of the waveform. How far does light travel in one period ? Express your result in meters and in feet. Draw a few cycles of a 20 MHz square wave. Below the drawing sketch the light signal with a delay corresponding to a light travel time delay due to travel back and fourth the a mirror set 5 feet away.

Imagine a point source 2 meters from a one inch diameter lens with focal length 50 mm. Where does a ray from the source through the lens center pass through the focal plane (the plane 50 mm behind the lens and perpendicular to its axis) ? Compare with the point that a ray from the source that passes through the lens at its edge (12.7 mm from its center). Return to the original centerline ray. With that incoming ray fixed, imagine translating the lens 2 mm perpendicular to that ray. How far is the point at which that ray crosses the focal plane displaced ?

Suppose the speed of signal cable is increased in length by 8 meters and that the signal speed in the cable is $1.6 \times 10^8 \text{ m/s}$. Sketch the 20 MHz 'square wave' light signal before and after increasing the cable length by 8 meters. The actual cable signal speed is not expected to be $1.6 \times 10^8 \text{ m/s}$.

Equipment These items are suggested. If you have a better, cheaper substitute, please send your recommendation to: tank@usna.edu

Lens Centering Cell 1.00" P/N 2100 \$219 CVI Laser (800) 296-9541

*** The experiment can be run over short distances without the lens cell

=> 5 meters total path with > 10 mV light signal.

25 mm Diameter Lens F.L. 50 mm uncoated A32-477 Edmond Industrial Optics

*** recommended change: Increase the focal length to 75or 100 mm - easier alignment !

25 mm Diameter Visible Laser Diode Mirror A43-532 Edmond Industrial Optics (800) 363-1992

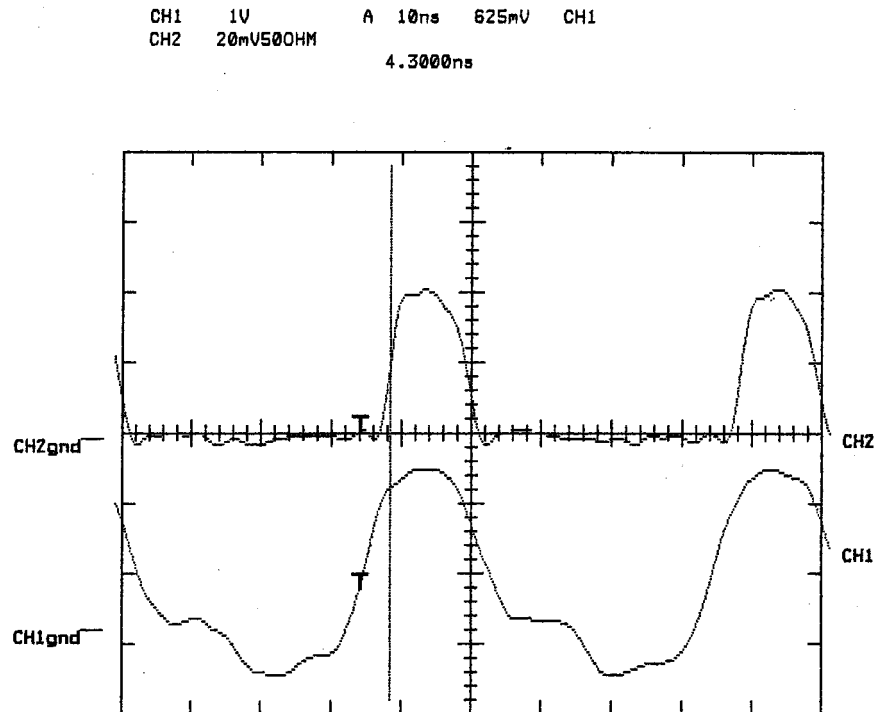
LASER, COLLIMATING LENS, BRASS Jameco #126244 Mfg Ref #U00-00544 7.95

LASER DIODE 650nm, 5mW, 3VDC Jameco #182932 Mfg Ref #ULD-655619.95

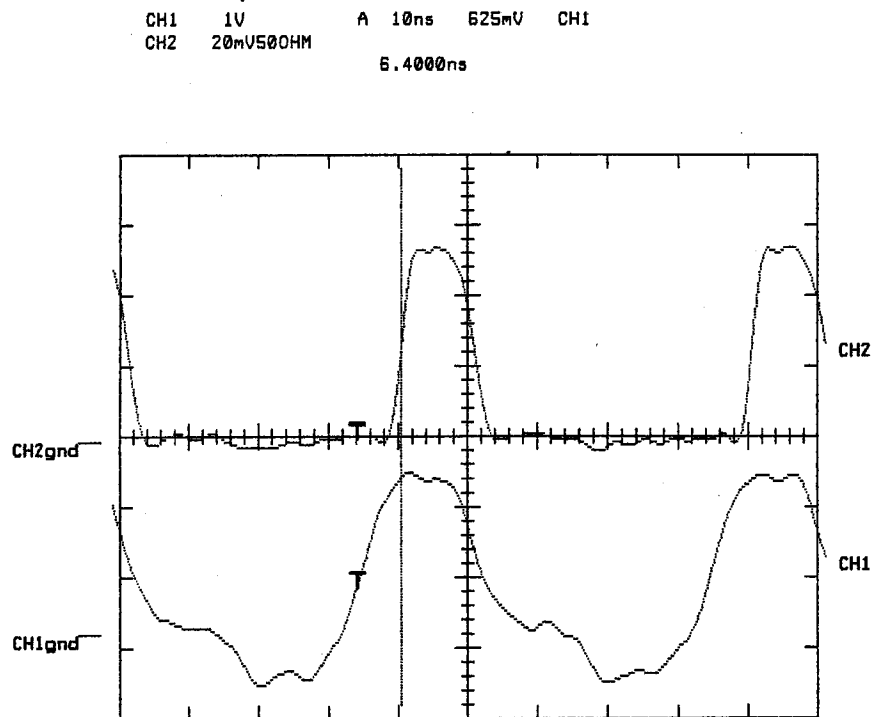
DET 210 fast photodiode detector assembly www.ThorLabs.com \$129

1" optics adjustable Kinematic Mount KM1HC www.ThorLabs.com \$47

Oscilloscope traces with mirrors at 0.00 m and at 0.30 m. Optical marker time 4.3 ns and 6.4 ns respectively. Speed estimate: $(2 \times 0.3 \text{ m}) / (2.1 \text{ ns}) = 2.86 \times 10^8 \text{ m/s}$. The vertical line to the left of center is the TIME cursor for the oscilloscope.

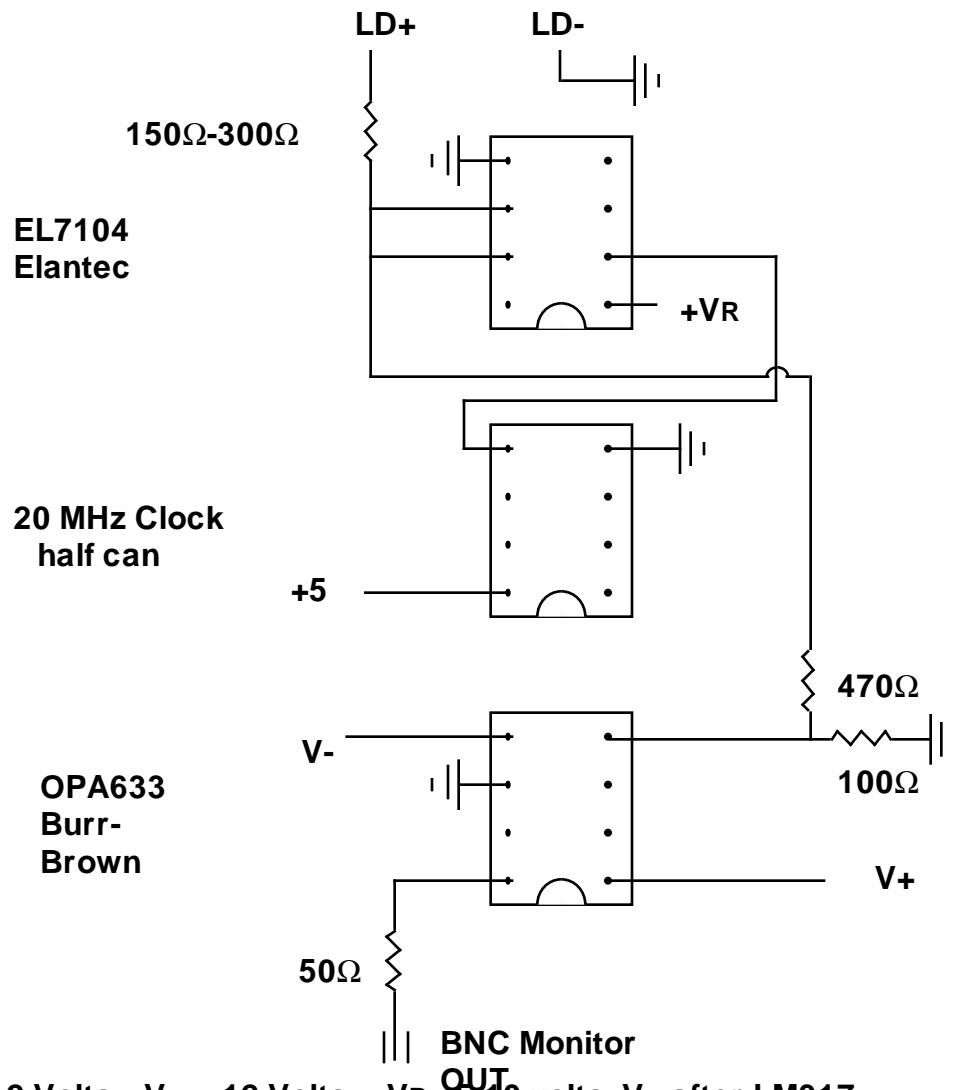


mirrors at $d = 0.00 \text{ m}$



mirrors at $d = 0.30 \text{ m}$

Set the regulated voltage V_R to 5 volts before connecting the laser diode.



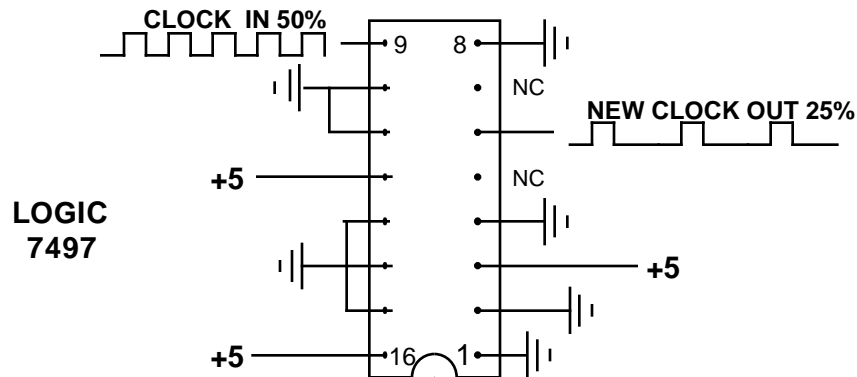
$V_+ = 12$ Volts $V_- = -12$ Volts $V_R = 5-10$ volts: V_+ after LM317 Regulator

V_+ , V_- and V_R each have a $1\ \mu\text{F}$ bypass capacitor connected to ground near where the voltage is input to the corresponding chip. A $0.1\ \mu\text{F}$ is recommended for the $+5\ \text{V}$ input to the clock.

Digikey is a source for the OPA633 (Burr-Brown, now TI) and for the Elantec (now Intersil) parts. One could try replacing the the EL7104 with another MOSFET driver from Elantec, Maxim or Micrel. The OPA633 is not an optimal choice. In a new design one might use a second MOSFET driver for the monitor out driver. If a proportional monitor is desired, try the Burr-Brown BUF634 in the 180 MHz mode.

NOTE: The OPA633 and BUF634 have different pin outs.

Rate Multiplier set to output every other input clock pulse.



The base rate out is 1/ 64 of the input rate. Pull the rate multiplier pins (Rn) high to multiply the rate. Ground rate pins not desired to be high. Each output pulse has the same duration as a single input clock positive pulse.

Pin 1=R2; Pin 2=R16; Pin 3=R32; Pin 4=R1; Pin 14= R4; Pin 15= R8

Above, pin 3 selects 32 times the 1/ 64 base rate.

Set to ground: Strobe, Enable & Clear - pins: 10, 11 & 13

Set to +5V: Cascade In - pin 12

Pin 9 - Clock In Pin 7 - New Clock Out to 7104

Pins 8 & 16 power the chip. Use a 0.1 μ F bypass cap pin 16 to Grnd.

25% DUTY CYCLE CLOCK OPTION: A 7497 logic chip, a binary rate multiplier, can be placed between the 20 MHz clock and the 7104 switch to select every other or every fourth clock pulse as the template for driving the laser. With a 25% duty cycle, the peak laser power can be increased to restore a 500 μW average power. The peak power should not be increased further as the duty cycle is reduced as the higher peak power can damage the laser diode. The lower duty cycle spaces the laser pulses more widely decreasing the chance for confusion when longer path distances are used. The increased peak power at 25% directly increases the signal level from the few tens of millivolts to the several tens of millivolts range.

The Texas Instruments SN7497N is available from Newark Electronics for \$3.53 each. There are many two chip solutions using more standard chips. DO NOT substitute a slower rate multiplier. Tell me if you find a faster one !

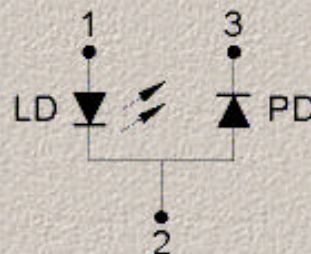
The principle of operation of a laser diode is not unlike that of a light-emitting diode. A p-n junction is forward biased with a current source. Charge carriers lose electrical potential energy in the depletion region and emit light, the color of which is determined by the band gap of the semiconductor material. The laser diode is different from the LED in that the lasing medium is contained between two partially-reflecting facets which form a cavity. A standing wave is formed in the cavity, plus stimulated emission, plus partial reflection,

Wavelength (nm)	Max laser power (mW)	Mode	Current (I _{th}) Typ (mA)	Current (I _{op}) Typ (mA)	Divergence (FWHM deg)	
					Parallel	Perpendicular
650	7	S	40	50	8	28
650	5	S	30	35	8	28

Note that 650 nm laser diodes have a relatively narrow operating band. The I_{op} is 25% and 17% above threshold for these cases. The operating range is wider for longer wavelength and 'better' laser diodes. The narrow operating band lead to the choice of a variable voltage drive circuit.

650nm / 7mW / 5.6mm package

Absolute Maximum Ratings (T_c=25°C)

Characteristic	Symbol	Value	Unit	 <p>TOLD9441MC 5.6mm Package Internal Circuit & Pin Connections</p>
Optical output power	P _o	7	mW	
Laser diode reverse voltage	V _{R(LD)}	2	V	
Photodiode reverse voltage	V _{R(PD)}	30	V	
Operating temperature	T _{opr}	-10 to +70	°C	
Storage temperature	T _{stg}	-40 to +85	°C	

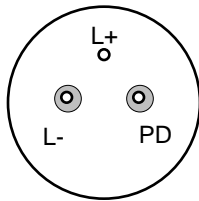
The case is point 2.

Laser Diode Assembly

LASER, COLLIMATING LENS, BRASS Jameco #126244 Mfg Ref #U00-00544 7.95
LASER DIODE 650nm, 5mW, 3VDC Jameco #182932 Mfg Ref #ULD-655619.95

Drop the laser diode into the barrel of the lens housing. Find a nutdriver with nut hole large enough to accept the diode leads and OD that fits inside the sleeve of the lens housing barrel. Start the keeper, the annular ring of metal that is beveled on one side. Beveled side in, start the piece by tapping with a small hammer. As soon as it is driven in by almost any small amount switch to using the nutdriver between the hammer and the keeper. Drive it home.

Solder leads to the diode leads. The laser anode L+ is common with its can. The remaining leads are for the laser cathode L- and the monitor photodiode. Forget about the integral photodiode. It appears to be too slow to be of value.



View from lead side.
the bottom

Tin the L+ and L- leads and then solder insulated lead wires to them. Use shrink tubing to insulate the leads and to cover the PD lead.

The case is electrically hot for the simple drive circuit described. Mount the laser diode in an insulating plastic ring to adapt it to the 1" size of the kinematic mount. Before installing the plastic lens in the lens housing add a shrink tubing jacket to the threaded lens cap for the lens holder assembly. It's just an extra level of protection. The housing of the DET 210 photodetector is at +12 volts which is high enough to blow the laser diode should it contact the lens housing. Insert the lens and spring and screw the cap on the lens housing.

Set $+V_R$ at +4.5 V and then connect the laser leads to the drive circuit. Increase the $+V_R$ slowly while monitoring the laser power. Remain below 600 μ W average power and 3 mW peak power.

Send to tank@usna.edu for the plans for a basic average power meter.

Major circuit changes: If the 7104 is chosen both to switch the laser and as a separate chip (in place of the OPA633) to monitor the laser voltage as it provides a timing mark signal only +5 and the laser $+V_R$ are required. One could use a single +12 supply with a +5 regulator and an adjustable regulator.

Consider 'doubling' the values of the resistors in the voltage divider that feeds the OPA633. The OPA633 is a \$10 chip and the input must be voltage divided to keep the output current below 60 mA driving a 50 Ω load. It is enough faster than the BUF634, that I recommend the 633.

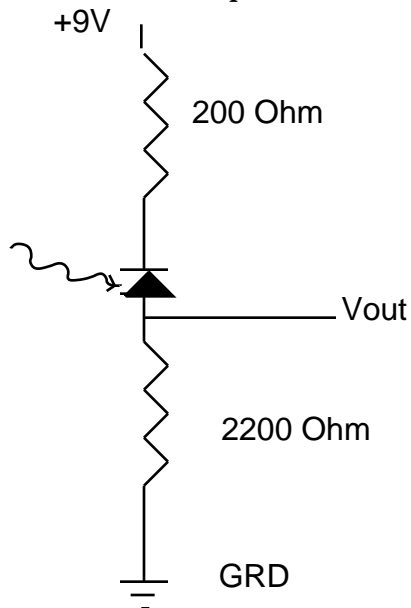
Detector Issues:

CONSTRAINTS: The laser is to be kept at or below $500\text{ }\mu\text{W}$ for laser safety considerations and the peak power is to be less than 3 mW to avoid damage.

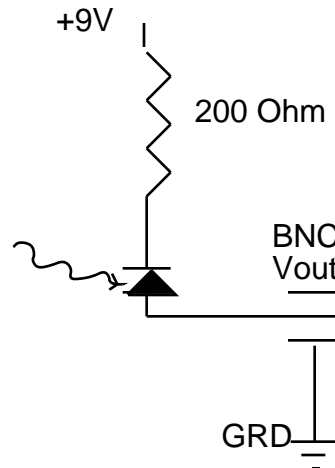
The systems are to operate in normally illuminated rooms. Low light levels, but not darkened rooms are better.

The recommended detector is a silicon PIN photodiode. Silicon photodiodes have a peak response of about 0.63 A/W at 900 nm , At 650 nm that drops to 0.45 A/W primarily because the 650 nm photon has a greater energy than does a 900 nm photon. The quantum efficiencies are not too different. The expected peak power in this experiment is $1\text{ mW} \rightarrow 0.45\text{ mA} \rightarrow 22\text{ mV}$ with a $50\text{ }\Omega$ termination. Any $< 3\text{ ns}$ risetime photodiode will work. ThorLabs sells the packaged detector for \$129 and the bare photodiode for \$48. It works well with a 9V reverse bias.

The larger, slower, cheaper ThorLabs photodiode can be purchased and terminated with a $2200\text{ }\Omega$ resistor to approximate a 1V per mW @ 650 nm power meter. Take care that the entire beam is incident within the active detector area. Note that the ThorLabs photodiodes have a sensitivity of about 0.45 A/W at 650 nm . Some diodes have sensitivities of only 0.3 A/W . Because of these variations and the possibility that part of the beam might miss the detector, the recommendation is to limit the measured power to $500\text{ }\mu\text{W}$.



Power Meter Detector: Uses 'slow' few mm^2 photodiode and $2200\text{ }\Omega$ resistor to give about 1V/mW at 650 nm . Output to a digital voltmeter.



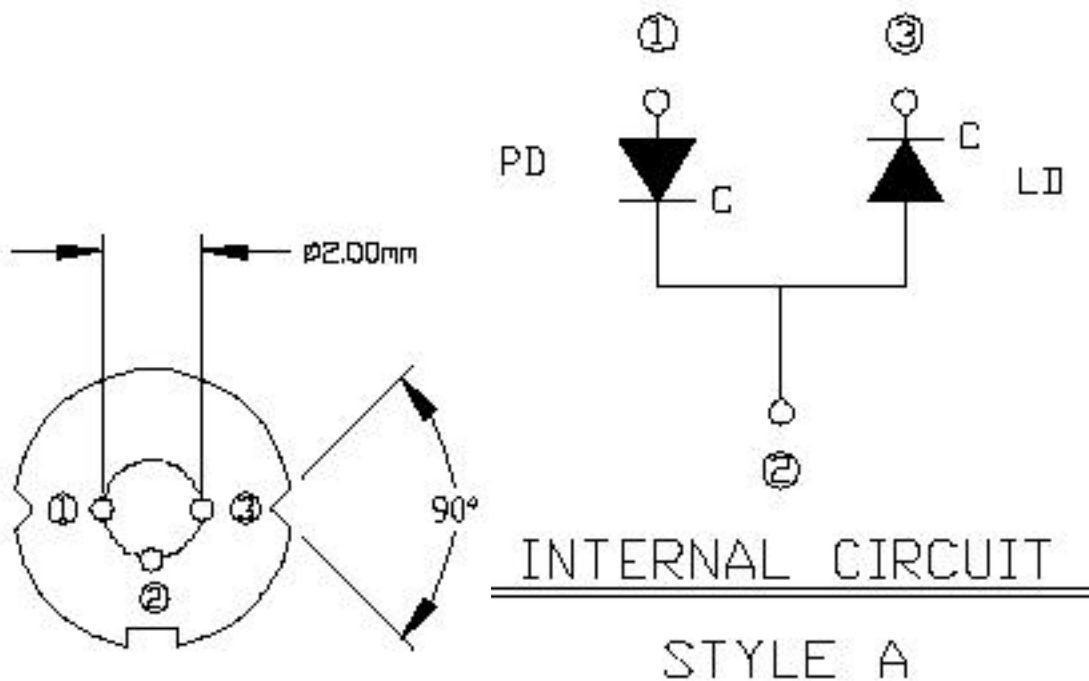
Fast detector uses small $< 1\text{mm}^2$ fast photodiode with risetime $< 4\text{ns}$. The BNC out goes to the $50\text{ }\Omega$ input of a scope. Sensitivity is about 22 mV/mW @ 650 nm .

resistor to give about 1V/mW at 650 nm. Output to a digital voltmeter.

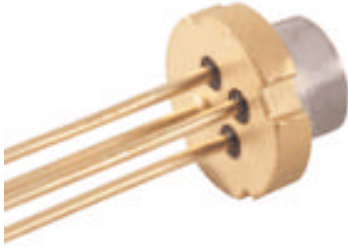
4ns. The BNC out goes to the 50 Ω input of a scope. Sensitivity is about 22 mV/mW @ 650 nm.

The lens centering cell - Is it necessary ? Not really, and, at 219\$, it is the most expensive component. The speed of light path can be over 5 meters and the signal level can still be acceptable. The small lens on the laser diode can be adjusted to provide adequate spot sizes. However, adjusting the laser diode lens walks the beam due to lens decenter. It's not too serious, but it happens. The lens cell and focusing optic is an alternate approach that can be used. I recommend a 75-100 mm FL lens rather than the 50 mm FL used here.

ALTERNATE LASER DIODE (STILL TRY THE JAMECO LENS)



Note: Most inexpensive laser diodes have a STYLE A pin connection pattern. It requires floating the diode case relative to ground if a simple positive voltage drive circuit is employed.



Absolute Maximum Ratings (T_c=25°C)		
CHARACTERISTIC	SYMBOL	RATING
Optical Output Power (CW)	P _o	5mW
LD Reverse Voltage	V _{R(LD)}	2V
PD Reverse Voltage	V _{R(PD)}	30V
Operation Case temperature	T _c	-10 to 60°C
Storage temperature	T _{stg}	-40 to 85°C

Optical Electrical Characteristics (T_c=25°C, P=5mW)				
CHARACTERISTIC	SYMBOL	MIN.	TYP.	MAX.
Threshold Current	I _{th}	-	30mA	55mA
Operation Current	I _{op}	-	35mA	60mA
Operation Voltage	V _{op}	-	2.2V	3.0V
Lasing Wavelength	λ _p	640nm	650nm	660nm
Beam Divergence (FWHM)	θ	5°	8°	12°
Beam Divergence (FWHM)	θ _⊥	24°	28°	35°
Monitor Current	I _m	0.07mA	0.25mA	0.5mA

The current from the monitor photodiode may be too small to provide a good signal when terminated at 50 Ohms. The 0.5 mA level would be usable, but a question of speed would remain.